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COST EFFECTIVENESS OF TUNGSTEN CARBIDE-CARBON FUEL CELLS

Heinz Carl, Harald Böhm and Franz A. Pohl

Translation of "Zur wirtschaftlichen Anwendbarkeit von Wolframcarbid/Kohle-Brennstoffzellen", Wissenschaftliche Berichte AEG-Telefunken, Vol. 46, No. 3-4, 1973, pp. 109-116,

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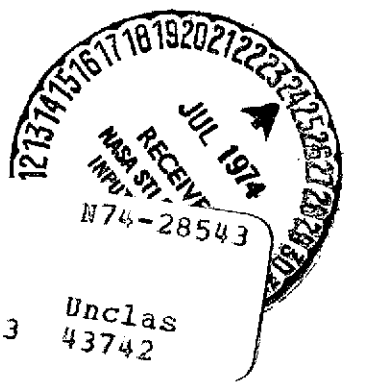

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16. Abstract

It is shown that the WC/C fuel cell offers an excellent alternative to conventional power sources for many applications. Three demonstration examples are presented for illustration: (1) electric trucks for industrial warehouse and plant applications; (2) fork lift trucks; and (3) power supply for radio link stations.

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COST EFFECTIVENESS OF TUNGSTEN CARBIDE-CARBON FUEL CELLS *

Heinz Carl, Harald Böhm and Franz A. Pohl

Introduction and Summary

In a previous work the calculation of the efficiency of fuel /109** cells was treated, and mention was made of the difficulty of assuming realistic future investment costs for fuel cell aggregates [1]. As the calculation was significantly affected by the nominal power of the individual generator unit, the magnitude of the annual production and the type of production process, many assumptions must be made which conceal in themselves more or less great uncertainties. It must also be considered that considerable savings are often possible in continuous manufacture through rationalization and continued development, and that these lead to simultaneous improvement of the product and reduction of its cost. As a typical example, let us refer here to the development in the last year in the field of semiconductor components (1). But since the other quantities which enter into the power generation costs with fuel cells, such as the efficiency of the cell and the

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(1) Among these aspects, one should note literature data which appear very low as compared to our own calculations. For instance, the investment costs specified in [2], $140/kW, refer to units with a nominal power of 20 MW. No more detailed information was given on the status of manufacture and the expected annual production.

** Numbers in margin indicate pagination of original foreign text.

fuel preparation, the type of fuel and the fuel costs, can largely be surveyed, it is possible to understand the influence of the height of the investment costs based on efficiency considerations and present them graphically. Here it appears that even with a considerable increase in the investment costs compared to those used for calculation in the previous work [1], the tungsten carbide-carbon fuel cell (WC/C cell) must be considered as an economically favorable alternative solution to conventional power supplies. This is shown with three examples, namely power supply of electric cars (Section 3), of fork lifts (Section 4) and of radio beacon stations (Section 5).

The investment costs are significantly determined by the size of the market which is equipped with fuel cells. Because, for one thing, the development of the tungsten carbide-carbon fuel cell is not yet completed, and also because, for example, the production numbers for fork lifts are rising continuously, more than doubling from 1961 to 1971, and other applications for fuel cells must be considered, final values can be estimated only after some years.

1. Effect of the Height of the Investment Costs for Fuel Cells on the Power Generation Costs

According to [1] the power production costs can be calculated as:

$$P = K_K + K_D + K_U \ (\mathrm{DM/kWh}) \tag{1}$$

Here, as in [1], the symbols are:

$$K_K = \frac{K_{inv} \cdot (\tau + i)}{Z_h \cdot f} \tag{2}$$

the capital costs;

$$K_B = \frac{k}{N_{in} \cdot f \cdot h} \qquad (3)$$

the operating and maintenance costs; and

$$K_U = \frac{K_{St} \cdot 860}{H_u \cdot \eta_t} \qquad (4)$$

the power conversion costs.

As in [1], the abbreviations used are:

K_{in} | investment cost of the fuel cell unit per kW installed power
τ | amortization factor (reciprocal of the lifetime in years)
i | interest factor = p/100; p = interest rate in %
Z_h | number of operating hours per year
f | load factor = generated power/installed power
k | hourly operating costs for the installed power
N_{in} | installed power in kW
h | operating time factor = $Z_h/8760$
K_{St} | fuel costs per kg (or m^3) of fuel
860 | rounded off electrocaloric conversion factor (1 kWh = $859{,}845 \cdot 10^3$ cal)
H_u | minimum heating value of the fuel in kcal/kg (or kcal/m^3)
η_t | over-all efficiency of the fuel cell unit at the load factor f (see Table 5)

Figure 1 shows the power generation costs for a tungsten carbide/carbon fuel cell as a function of the load factor with the investment cost as a parameter. The other data are listed in Section 2.1 of the previous work [1]. From the figure we can see how the power generation costs depend on the investment costs.

If we consider especially the value at load factor f = 1, we see that doubling of the investment cost from DM 1,200.-- to DM 2,400.-- results in only increasing the power generation costs by the factor 1.33. Under the same conditions, multiplying the investment costs fourfold to DM 5000.- causes the cost per kilowatt hour generated to double. Even with a ten-fold equipment cost of DM 12,000.--, the cost per kilowatt hour rises only by fourfold (at f = 0.5 the factors are 1.6; 2.9 and 6.5).

Figure 2 shows the same relations in case methanol at 0.30 DM/kg or taxed gasoline at 0.66 DM/kg is used instead of untaxed gasoline. As assumption of these prices, referred to the energy content of the two fuels, gives equal fuel costs, the curves apply for both fuels. In calculation of this family of curves, the operating and maintenance costs were also determined differently. As is often common in technology, they were referred to the invest- /110
ment costs. Here

$$K_B = \frac{K_{Inv} \cdot i^o}{Z_h \cdot f} \text{ (DM/kWh)} \qquad (3a)$$

with i^o as the operating cost factor. In the calculation, we use for this 0.05, corresponding to 5% annual operating and maintenance costs. Due to the large proportion of fuel cost in the power generation cost, the change of the investment cost with these operating conditions is even less notable than in the first example. If the system costs are increased tenfold, for f = 1, the cost per kilowatt hour only doubles (only to 4.3 times as much at f = 0.5).

In the following application examples for tungsten carbide-carbon fuel cells, the investment costs of the fuel cell unit are taken as 5,000.-- DM/kW. This total appeared in the calculation for a small to moderate serial production for unit sizes of 1 to 5 kW. Because of the unavoidable range of variation, the calculated

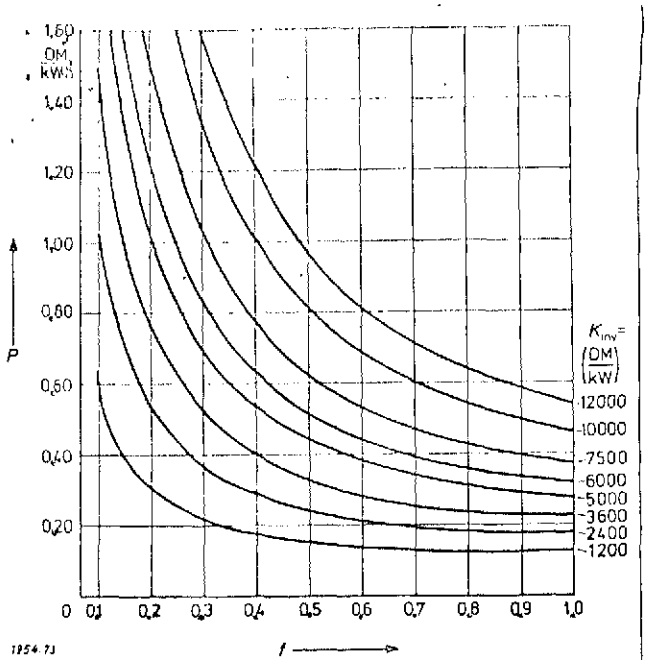

Figure 1. Power generation cost P of a WC/C cell as a function of the load factor f with the investment cost, K_{inv}, as the parameter.
($r = 0{,}2$; $i = 0{,}1$; $\bar{Z}_h = 8000$ h; $k = 0{,}01$ DM/kW ; fuel: untaxed gasoline; $K_{St} = 0{,}15$ DM/kg; $H_u = 10000$ kcal/kg; η_t see Table 2 from [1])

cost was rounded off to a full thousand DM. The 1,200 DM/kW which was assumed in the previous work should be realizable at appropriate rational large scale production and units of greater power. Even if one supposes that the assumptions on which the calculation are based must be corrected, the basic conclusions remain unchanged because, as the figures show, the investment costs have only a less than proportional influence on the power generation costs.

2. Characteristic Properties of Some Power Sources

In the question of the usefulness of a device, one must consider not only the costs but also the special characteristics of it. Some typical peculiarities of tungsten carbide-carbon fuel cells, lead storage batteries, and Diesel units are presented

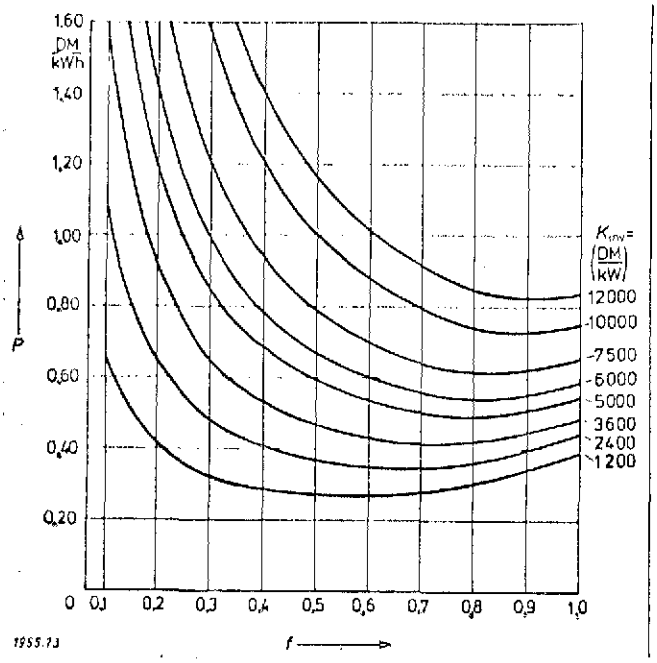

Figure 2. Power generation cost, P, for a WC/C cell as a function of the load factor, f, with the investment cost, K_{inv}, as the parameter.

(Calculation of the operating costs, K_B, according to Equation (3a) with $i^o = 0.05$; fuel: methanol, K_{St} = 0,30 DM/kg, H_u = 4660 kcal/kg for taxed gasoline, K_{St} = 0,66 DM/kg, H_u = 10000 kcal/kg)

in the following summary. The predictions apply for unit sizes equivalent to fuel cells up to about 10 kW.

2.1 Tungsten carbide - carbon fuel cell

Fuel cells are largely noiseless and friendly to the environment. Because they are independent of the electrical network, they can also be used independent of location and, if necessary, mobile. As the tungsten carbide-carbon fuel cell can be operated with hydrogen-containing cracked gases, it can be adapted to various fuels such as methanol, gasoline, etc., by connecting in an appropriate reformer. Tungsten carbide - carbon fuel cells require

little maintenance. Long term operation is possible for a long time (eventually several years). The fuel cell can easily be matched to the load through series and parallel connection. Because of the relatively soft voltage characteristic, direct current regulators or voltage-stabilized alternator convertors may be required in some applications. The temperature dependence of the output power of the fuel cell is similar to that for the lead storage battery. In intermittent or interrupted operation with long waiting periods and low ambient temperature, additional heating can make the full power of the cell available at any time.

2.2 Lead Storage Battery

Batteries are also noiseless. With large units, an acid mist is produced on charging. This makes necessary a significant expense for ventilation of the charging stations and perhaps additional corrosion pretection. To charge the battery, it must be connected to a supply net or a special charging generator. In this relation, a battery depends on its location. Mobile use with discharging is possible. The maintenance cost for secondary batteries is relatively high, primarily because of the necessary charging. From this it appears that the necessary changing of batteries puts a considerable load on the costs for long-term operation. The maintenance costs are more favorable for batteries used in buffer operation, as the 'net' to be buffered and the battery are continuously connected in parallel, aside from failures, and because of the low charging current, no significant amount of gases is produced in the cells. The lifetime of a lead storage battery is 1,000 to 1,500 charge-discharge cycles / 111 without change of plates. Starter batteries last 2.5 to 4 years, depending on the load. Matching to the load is achieved by connecting cells in series and by selection of types. In the fully charged state, the voltage characteristic is steeper than for the fuel cell. It is strongly dependent on the state of

charge, the battery temperature, and the age of the battery. As for fuel cells, an AC converter is necessary for connection to loads that require alternating current.

2.3 Diesel Unit for Long-Term Operation

Depending on the location, Diesel units can be disturbing because of the operating noise and the waste gases. They are independent of the electrical network. Mobile use depends on the size of the unit. The maintenance cost for ensuring continuous operational readiness is high. In many cases a reserve unit of the same design size is necessary to bridge over maintenance periods and possible failures. The lifetime and the length of the maintenance interval are determinable through corresponding cost, depending on the application. In general, they rise with the size of the unit. Matching to variable load is possible within wide limits, but continued low-load operation must be avoided, if necessary by connecting an artificial load of up to 30% of the unit power.

3. Efficiency Comparison of Tungsten Carbide-Carbon Cells and Lead Storage Batteries for Use in an Electric Car

An electric car is one of the applications in which direct replacement of the previously used lead battery by a fuel cell unit appears possible without special voltage stabilization. According to statistical statements, 6,100 electric cars and trains have come newly into operation in the Federal Republic in the last ten years (1962 to 1972). As we can figure on a lifetime of more than ten years for the vehicle, this gives a total of some 8,000 units at present in the Federal Republic. The electric cars and most of the trains are equipped with units of 1 to 5 kW. Statistical figures on the daily operating hours are not known. It can be estimated that 80% of the vehicles are

used on more than one shift, and a considerable part of them are used over long periods on three shifts. Aside from roads and mail, a large number of these vehicles are operated in port installations.

3.1 Data for Battery Operation

The calculations are based on a 2 kW electric car. The capital costs were determined according to Equation (2). As we start directly from electrical energy, we obtain for the power conversion cost:

$$K_U = \left| \frac{k_{el}}{\eta_{el}} \right| \qquad (4a)$$

with k_{el} = cost of the charging process per kWh
and η_{el} = over-all efficiency of the charging process, considering the transformer and the charger rectifier.

3.1.1 Bases of calculation with the lead storage battery

In the cost comparison here we use only the amounts for batteries and charging equipment, as the other costs are independent of the type of power source. The price of a single device is used for the charger. For the charging station of a large transport park, of course, the proportional charger cost per electric car will be smaller, but there are additional costs for the charger room and its ventilation, giving compensation. Also, the exact investment costs for special charger stations are different in some cases and cannot, therefore, be used for this comparison.

In case the battery set must be exchanged during the operating period of the electric car, the investment costs increase by the amount of the replacement battery and a special lifting gear which must be used in addition to a fork lift or another

lifting device for changing batteries.

Table 1. CALCULATION VALUES FOR ELECTRIC CAR WITH LEAD STORAGE BATTERY

Installed power		2 kW
Battery capacity (K_5) at maximum of 80% discharge		150 Ah; 80 V
Write-off period		5 years
Investment cost for 2 kW		DM 6021.—
Battery, including pan		DM 1296.—
Charger		DM 300.—
Lifting equipment for changing		DM 0%
Interest on capital		
Cost of charging power		0.06 DM/kWh
Efficiency:	Battery	65%
	Charger	85%
	Over-all	55%

3.1.2 Calculation of the maintenance costs

In calculating the maintenance costs of battery operation it must be considered whether there will be battery changes, or whether they can be avoided and the batteries can be charged in the car.

Simple maintenance includes connecting the battery to the charger, opening of the cell covers and occasionally testing of the acid level and acid density, greasing of the pole connectors, etc. About 15 minutes per charge is required for this work. At an hourly cost of DM 28.-- (including all bonuses), which we must figure on today, we get DM 7.-- per charge. If we suppose that

the battery is completely discharged (5 hours at 2 kW ≙ 10 kWh), this gives DM 0.70 per kilowatt hour. To make the calculation easier to follow, this cost is used even when the battery is fully recharged overnight after partial discharge so that the full battery capacity will always be avilable at the start of work. As the maintenance work depends principally on the charging itself and not on the amount of charging, partial charges would give higher maintenance costs per kilowatt hour.

Assume that a battery change takes 15 minutes. Since a lifting device and the special lifting equipment mentioned are needed, we must figure on an hourly cost of DM 50.--. As above, in the determination of the charging cost, we get DM 12.50 for each change and, from that, DM 1.25 per kilowatt hour and change, including the maintenance costs for the charging to get DM 1.95 per kWh for battery change with battery charging. Partial discharges would seldom occur here.

For one and two shift operation, there can also be a case in which there is an additional charge every one or two battery changes. For this, we get as maintenance costs:

- 1 change + additional charge: $\frac{1}{2} \cdot (1{,}95 + 0{,}70)$ DM/kWh ≙ $= 1{,}33$ DM/kWh
- 2 changes + additional charge: $\frac{1}{3} \cdot (2 \cdot 1{,}95 + 0{,}70)$ DM/kWh ≙ $= 1{,}53$ DM/kWh

3.1.3 Relation between the operating hours, the load factor and the charge with or without battery change

The operating conditions are of decisive importance in evaluation of the efficiency of battery-supplied or fuel-cell-supplied electric cars. In operation with sufficient pause times for recharging the battery, the total costs are relatively more favorable for the battery electric car than when a reserve battery with its higher maintenance costs must be included in the calculation.

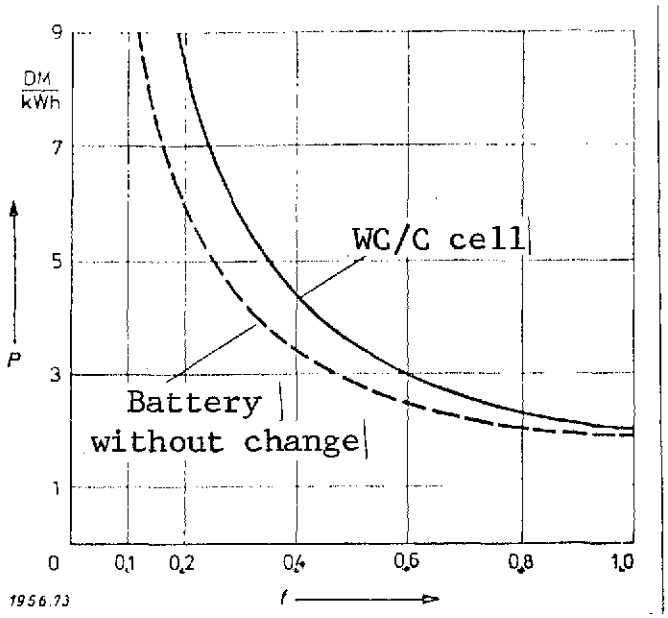

Figure 3. Comparison of power generation cost, P, for an electric car with supply from a WC/C fuel cell (methanol/air) and a lead battery at Z_h = 1,000 hours.
Solid line: fuel cell; Broken line: lead battery.

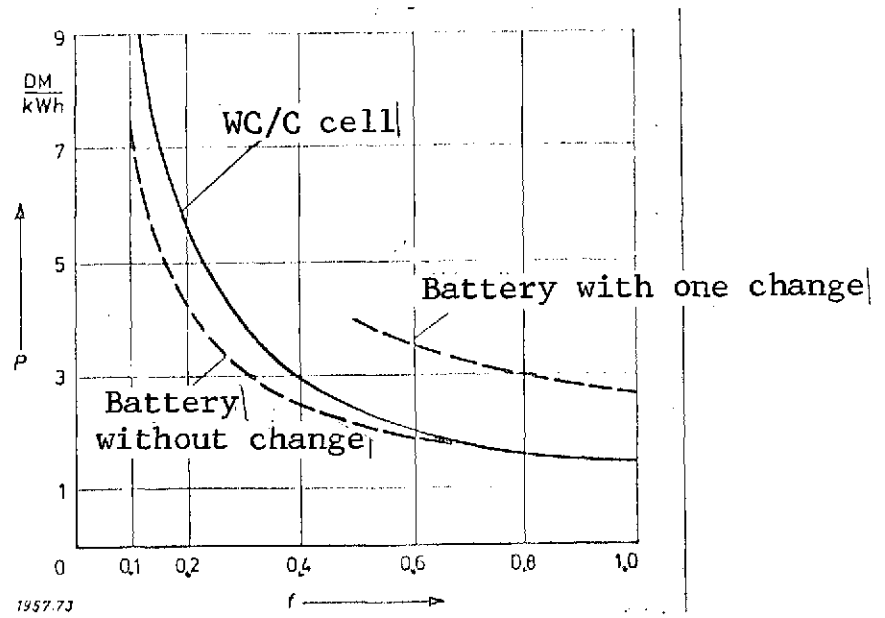

Figure 4. Comparison of the power generation cost, P, for an electric car with supply from a WC/C fuel cell (methanol/air) and a lead battery at Z_h = 1,500 hours.
Solid line: fuel cell; Broken line: lead battery.

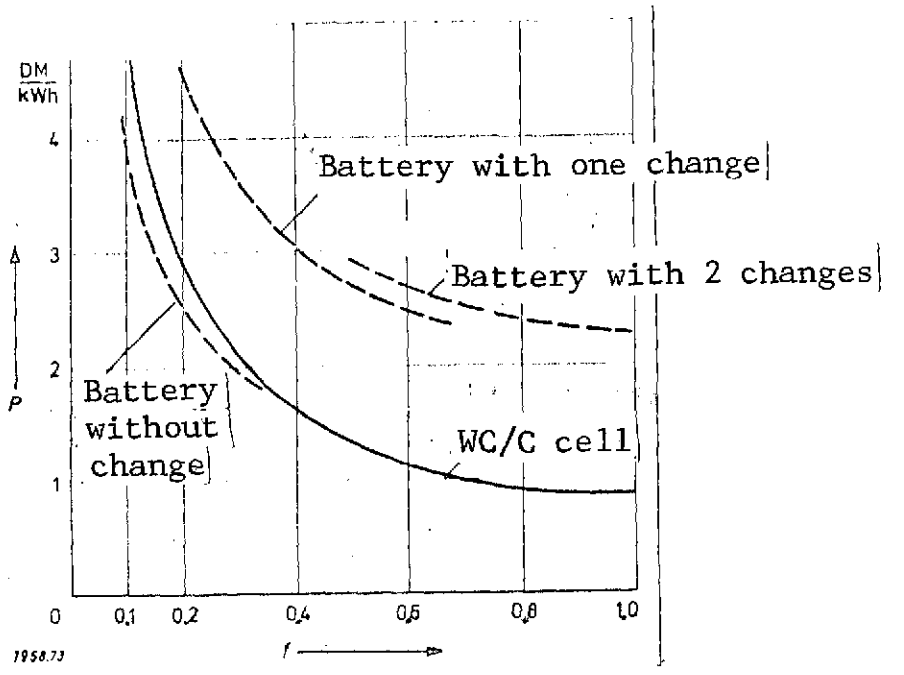

Figure 5. Comparison of power generation cost, P, for an electric car with supply from a WC/C fuel cell (methanol/air) and a lead battery at Z_h = 3,000 hours.
Solid line: fuel cell. Broken line: lead battery.

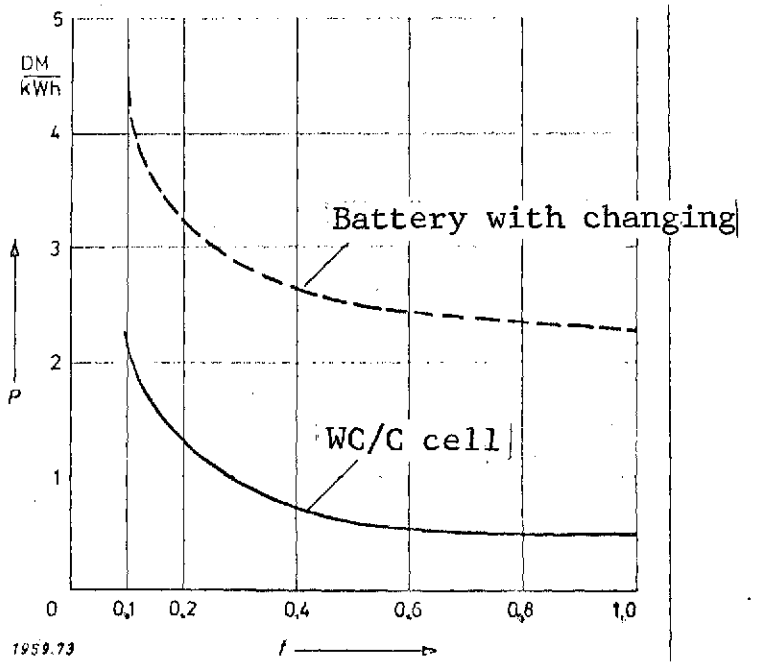

Figure 6. Comparison of the power generation cost, P, for an electric car with supply from a WC/C fuel cell (methanol/air) and a lead battery at Z_h = 8,000 hours.
Solid line: fuel cell. Broken line: lead battery.

In order to make this relation clear, the cost comparison was made for operating hours

Z_h =	1,000 hours (Figure 3)	1,500 hours (Figure 4)	3,000 hours (Figure 5)	and	8,000 hours (Figure 6)

If we assume 200 working days per year in normal operation, then 1,000 operating hours per year means five hours operation daily. Here, the battery capacity is sufficient to get by without a battery change at all load factors, so that a maintenance cost of K_B = 0.70 DM/kWh can be used, independent of f.

Z_h = 1,500 hours corresponds to one-shift operation with 7.5 hours operating time daily. One battery charge suffices only up to a load factor of f = 0.67. For greater f values we must consider the reserve battery and the lifting equipment and maintenance costs for single changes of the battery (1.33 DM/kWh) along with the cost of the reserve battery.

For 3,000 operating hours annually the limit for a single battery change is f = 0.33. Above f = 0.67 there must actually be two daily battery changes, so that the maintenance costs rise to 1.53 DM/kWh. Y13

At Z_h = 8,000 hours we have 22 hours per day for 360 days per year. From this it follows that direct intermediate charging of the battery is impossible for reasons of time. Thus the investment cost always includes at least one reserve battery and the lifting equipment. The maintenance costs are 1.95 DM/kWh. The change from operation without to operation with battery change and from single to double battery change always makes a step in the cost curve. As the changes in practice do not occur exactly at the maximum load factor, the curves in Figures 3 to 6 are plotted to overlap.

3.1.4 Cost Calculation for Battery Operation

The calculation of the power production cost, P, follows from operation of the electric car without battery change as K_{inv} = 3658.50 DM/kW. With battery change the investment cost rises to K_{inv} = 6819.-- DM/kW. The maintenance costs given in Section 3.1.3 are used as the operating costs K_B.

As the result of the calculations, the power generation costs for battery-supplied electric cars are plotted as broken lines in Figures 3 to 6.

3.2 Data for Supply with Tungsten Carbide-Carbon Fuel Cells

The calculation of the power generation costs for supplying the electric car from a tungsten carbide-carbon fuel cell is done with Equations (1, 2, 3a, 4).

3.2.1 Bases of Calculation for Fuel Cell Operation

Table 2 shows the calculation data for the power generation cost, P, for supply of the electric car from fuel cells. The efficiency η of the fuel cell is set constant at 24% up to a load factor of f = 0.8, as it can be assumed that lower load factors in electric car operation arise only through averaging over the pause periods and not through extended operation at partial load. For f = 0.9, η becomes 0.2, and for f = 1 we use η = 0.16 (see Table 5). For good comparability, the results of the calculation are plotted as solid lines in Figures 3 to 6.

Table 2. CALCULATION VALUES FOR ELECTRIC CARS WITH WC/C CELLS

Installed power	2 kW
Writeoff period	5 years
Investment cost for 2 kW	DM 10,000.--
Interest rate	8%
Fuel: methanol	0.30 DM/kg
Heating value for methanol, H_u	4,660 kcal/kg

3.3 Evaluation of the results

The figures show the great influence of battery changes on costs for battery operation. At partial load without battery change the power generation cost for operation with the lead battery is more favorable than for the fuel cell. But one can assume that electric cars are seldom operated in this load range over long periods. At somewhat fuller utilization of the battery capacity, that is, at Z_h = 1,000 hours for $0.7 \leq f \leq 1$, at Z_h = 1,500 hours for $0.5 \leq f \leq 0.67$ and at Z_h = 3,000 hours for $0.25 \leq f \leq 0.33$ the costs are largely the same for fuel cell and battery operation. The cost advantage of the fuel cell appears in the operating conditions with battery change. The power generation costs are halved, for instance, for one-shift operation, and are reduced even below 25% for long-term operation.

4. Use of Fuel Cell Units for Power Supply in Fork Lifts

Fundamentally, electrically driven fork lifts put similar requirements on the power supply as do electric cars. To be sure there are usually two (generally different) drive motors. One is used for locomotion and the other for lifting. The basic results from the previous section with respect to potential use of fuel cells for power supply in electric cars, accordingly, also apply

for fork lift power supply. Thus, we must expect curves very similar to those in Figures 3 to 6, and it would be repetitious to show them. Table 3 contains examples for fork lifts of the usual sizes.

Table 3. DATA FOR FORK LIFTS.

Lift force	Drive motor	Lift Motor	Battery
0,6 t	1,5 kW	1,6 kW	24 V 300 Ah
1,0 t	2,2 kW	2,4 kW	24 V 500 Ah
3,5 t	11 kW	8 kW	80 V 600 Ah
5 t	11 kW	9 kW	80 V 700 Ah

The great majority of the fork lifts in use are in the range of 1 to 2 tons lift force.

According to statements from the VDI [Society of German Engineers] expert group on Material Flow and Transport Technique in Dusseldorf, there are an estimated 120,000 to 150,000 fork lifts in the Federal Republic, about 60% of which use combustion engines. From the requirement for environmental protection, we must expect that the trend to electric operation will prevail strongly, especially for operation inside buildings. Very high-capacity electric lifts (even in load classes of 2 to 4 tons) are already being offered.

According to previous experiments, the corridor transport vehicles (fork lifts) in German plants operate about 10% in three-shift operation and 25% in two-shift operation. In order to ensure smooth shift operation, one battery per shift is generally required.

5. Economic Comparison of Power Supply for Radio Directional Stations Using Diesel Units or Tungsten Carbide/Carbon Fuel Cells

While, in the preceding examples for power supply of electric cars and fork lifts, one could work on the basis of a simple exchange between the two power supplies, with power supply for radio directional stations one must design the whole system basically differently, depending on whether Diesel units or fuel cells are to be used for the supply. A direct cost comparison on the basis of the same nominal power for the supply would, therefore, be erroneous.

For use of fuel cells to operate electric cars one must assume a certain number of vehicle types, all of which will be produced in large numbers. For power supply to radio directional stations, on the contrary, the individual operating conditions will be so different that only a few of the same units will be needed. Thus the following example calculation can be considered only as a typical case of comparison.

5.1 Comments on Supply of a Radio Directional Station with a Diesel Generator

For radio directional stations, we must distinguish between different groups of loads. On one hand, the radio transmitter and receiver units must be supplied with uninterrupted power. On the other hand, there are loads connected to the power supply for which the high cost of uninterrupted supply is not justified. The uninterrupted proportion of the load is called the main load / 114
and the remainder the secondary load. The main load is often only a small fraction in proportion to the installed power, as two examples of designed systems show:

System 1: Main load at present 285 W (DC); in final development 570 W.
Installed capacity: 2 units of 19 kVA each (3 phase)

System 2: Main load at present 1 kW (DC); in final development 2 kW.
Installed capacity: 2 units of 24 kVA each (3 phase).

The relatively large installed capacity arises primarily from special requirements for battery and charger equipment for uninterrupted operation as well as from the necessity for air-conditioning the radio equipment rooms. In both cases, there is also a capacity reserve provided for expansion of the complete system.

The double equipping of the systems with Diesel units is necessary both for freedom of the supply from interruption and to extend the maintenance interval. References [3, 4] contain more detailed information on the general course of operation. The following calculations are based on the data for System 1.

5.1.1 Bases of Calculation for Diesel Unit

For the system considered as an example here, a main direct current load of 285 W (570 W) must be provided free of interruption. The system is made up of the following components and equipment:

- two Diesel 3-phase units of 19 kVA each (corresponding to 15 kW each at $\cos\varphi = 0{,}8$)
- special equipment for maintenance-free long-term operation, including long-term lubricant supply
- equipment for fuel supply
- equipment for artificial loading (so that the Diesel unit has an adequate minimum load in any case)
- automatic cutoffs for both Diesel units
- two main batteries with their automatic chargers
- automatic DC equipment for the operationally necessary

switching on the DC side.

The investment costs for the complete system run about DM 90,000.-- , unpacked at the plant. The cost for transport, erection, packing, etc., depend on the location of the system. As we will get proportionally similar amounts in DM/kWh for systems with Diesel units and with fuel cells, they are neglected in both cases.

5.1.2 Comments on the Design and Operation of the System

The two Diesel units installed each run one week, alternately. Switching from one to the other is done with the automatic cutoff unit. As reserves were considered for a later expansion, they are now operated at about 10 kVA ($\hat{=}$ 8 kW). The minimum load which can be attained with sound long-term Diesel operation, is about 6 kVA ($\hat{=}$ 5 kW), independent of the necessary load. This is maintained by means of the artificial load equipment. In this way the system runs with a load factor, f, between 0.15 and 0.25 in relation to the installed capacity.

The extreme operating conditions exist when only the main load is being supplied by the unit. Then generation of some 5 kW is compared to an effective useful load of 285 W (570 W in the final development). The approximately 4.7 kW (4.4 kW) which are converted in the artificial load is a pure loss.

5.1.3 Data on Operating and Fuel Costs

On the basis of many years of experience with the systems, it is justifiable to figure on 5% of the unit cost as the annual operating cost of the Diesel unit. For the other parts, such as the switching equipment, batteries, charger, etc., about 1% of the investment cost has been spent annually for maintenance in the

years since the beginning of operation. For simplicity, in each case 50% of the investment cost was used for the unit and the remainder of the system.

The cost for consumption of fuel and lubricants is very dependent on the location of the system. For instance, the cost of Diesel oil in Venezuela is only a fraction of the cost in the Federal Republic. If we figure with the German cost of 0.54 DM/kg at H_u = 10,000 kcal/kg, then about DM 13,500.-- is spent annually for fuel costs for the system at f = 0.25. Lubricant costs are approximately DM 4,400.-- per year.

5.1.4 Cost Calculation for Operation with Diesel Units

As the system runs without interruption, we take 8,760 hours for Z_h. Thus Z_h drops out as a parameter in this example. We figure on a writeoff period of n = 10 years and an interest rate of 8%, obtaining:

$K_{inv_{total}}$ = 90,000.-- DM
at N_{inst} = 30 kW
so that K_{inv} = 3,000.-- DM/kW.

The load factor, referred to the installed power, varies only from 0.15 to 0.25 (in the final development to 0.5).

The operating costs are calculated as 5% of the unit cost and 1% of the other investment cost, in addition to the proportionate lubricant consumption. (As the dependence of the lubricant consumption on the load factor is not known, the calculation is made with a constant rate. From 4,400 DM for 70 MWh/yr one obtains 0.063 DM/kWh.)

The efficiency is required to calculate the power conversion cost, K_U. At half load for one unit, corresponding to f = 0.25, we can take $\eta_t = 24{,}5\%$. For f = 0.2 we can calculate with $\eta_t = 21\%$ and with $\eta_t = 17{,}5\%$ for f = 0.15. From this we get the power generation costs, P_f, for the Diesel unit:

$$P_{0,15} = (0{,}411 + 0{,}131 + 0{,}273)\ \text{DM/kWh} = 0{,}81\ \text{DM/kWh},$$
$$P_{0,20} = (0{,}309 + 0{,}114 + 0{,}221)\ \text{DM/kWh} = 0{,}64\ \text{DM/kWh},$$
$$P_{0,25} = (0{,}247 + 0{,}104 + 0{,}186)\ \text{DM/kWh} = 0{,}54\ \text{DM/kWh}.$$

The power generation costs, P_f, are shown in Figure 7 as a function of the load factor, f, referred to the installed power. The range $0{,}15 \leq f \leq 0{,}25$ (in which the system is currently being operated) is shown in solid lines, and the remainder of the curve in dashed lines.

Because of the different design of the total system with respect to capacity, for comparison of efficiency, we are interested not only in the power generation costs but also the total costs of power production per year. They are designated as P*. The annual power production costs, P*, shown in Figure 8, are calculated from the installed power, the load factor, the operating hours and the power generation costs. The nature of the presentation in Figure 8 corresponds to that in Figure 7.

5.2 Comments on Power Supply for the Radio Directional Station with a Fuel Cell

Equipping a radio directional station with fuel cells for power supply will give defensible costs only if they are used only to cover the consumption by the main load and a small part of the secondary load which has been common, such as the aircraft

warning lights for the antenna and similar parts of the system. Stations without continuous operational personnel come into consideration, and then, with appropriate design of the radio equipment, no special air conditioning is needed. A reserve for later expansion of the system is not necessary in use of fuel cells, as the investment costs per kW installed capacity in the period of use depend only slightly on the unit size, so that no significant savings can be made by a single installation of a large battery of fuel cells. In power supply for a radio directional station the expansion of the cells will be done only when it is needed. / 115

For the radio directional station with a main load of 285 W we can figure on some 300 W for the aircraft warning lights. If we make the same addition for other necessary loads, we arrive at a connected value of about 1 kW. If we establish that this power is to be attained at a load factor of $f = 0.7$, because of the redundance which must be considered, this gives an installed power of 1.4 kW. The main load then corresponds to the load factor $f = 0.2$. Therefore the fuel cell is generally operated with $0.2 \leq f \leq 0.7$. If one designs the battery so that a voltage of 27.5 V is produced at $f = 0.2$, then one still gets 21 Volts at $f = 1$. This is just the range in which the radio directional equipment works without voltage stabilization [4]. The safety factor for freedom from interruption is adequate, with the factor of 5 (main load operates at $f = 0.2$), so that no reserve unit is needed.

5.2.1 Data and Cost Calculation for Fuel Cell Operation

On the basis of the comments made in the previous section, we obtain the values summarized in Table 4 for calculation of the power generation cost P and the annual power cost P^* for fuel cell operation of a radio directional station. Table 5 shows the

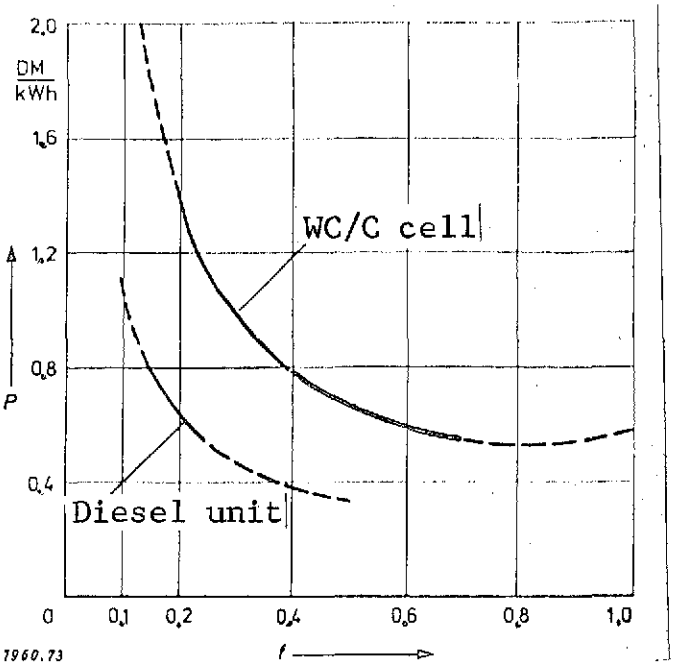

Figure 7. Comparison of power generation costs, P, as functions of the load factor f for a radio directional station. (As only one of the two Diesel units works at a time, that curve ends at f = 0.5.) The interval in which the systems normally operate, $0.15 \leq f \leq 0.25$ for the Diesel unit and $0.2 \leq f \leq 0.7$ for the fuel cell battery, are shown in solid lines, with the rest of the curve dashed. The part of the fuel cell curve at which the main load and the aircraft warning lights are supplied as the minimum load is drawn more strongly.

Table 4. CALCULATION VALUES FOR POWER SUPPLY OF A RADIO DIRECTIONAL STATION WITH WC/C CELLS.

Installed power:	1.4 kW
Writeoff period:	5 years
Interest rate:	8%
WC/C cell investment cost	5,000 DM/kW
Investment cost for additional circuitry for uninterrupted supply of the main load:	1,500 DM/kW
Fuel: methanol:	0.30 DM/kg
Heating value for methanol, H_U:	4,660 kcal/kg
Operating hours, Z_h:	8,760

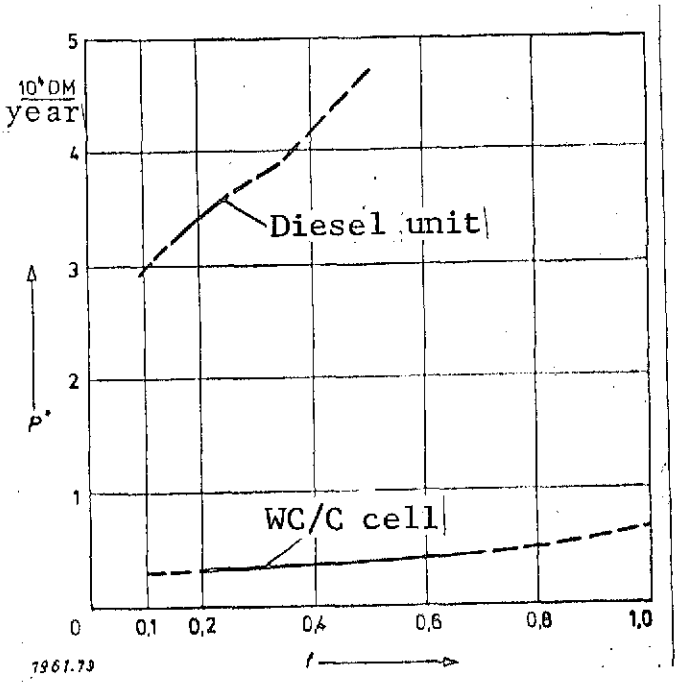

Figure 8. Comparison of the annual power cost, P* as a function of the load factor, f, for a radio directional station. (As only one of the two Diesel units works at a time, that curve ends at f = 0.5.)
The interval in which the system normally operates, $0,16 \leq f \leq 0,26$ for the Diesel unit and $0,2 \leq f \leq 0,7$ for the fuel cell battery, are drawn in solid lines, and the remainder of the curves in dashed lines.

Table 5. RELATION BETWEEN LOAD FACTOR AND EFFICIENCY FOR A WC/C CELL.

Load factor f	Efficiency η_f
0,1	0,32
0,2	0,34
0,3	0,36
0,4	0,33
0,5	0,32
0,6	0,29
0,7	0,27
0,8	0,24
0,9	0,20
1,0	0,16

dependence of the efficiency, η, on the load factor.

Methanol is also used as the fuel in this example because in this case the cost of the reformer can be calculated on the basis of the work done and the efficiency is known. To be sure, cracking gas reformers for hydrocarbons (such as gasoline, Diesel oil, or the like) are not yet known for the civilian sector in sizes which could supply a 1 to 5 kW fuel cell unit. But their development should not encounter any fundamental problems. Granted, a calculation of the investment cost would be possible only with correspondingly great uncertainty, and statements about efficiency cannot be made at all now. But one can assume that a reformer for hydrocarbons is more difficult and, therefore, more costly than a methanol reformer, because the reaction temperature is higher. If hydrocarbons can be used as fuels in special cases, and if they are available without significant tax load, they will allow the costs calculated for methanol operation to be reduced.

The power generation costs, P, for power generation by fuel cells are plotted in Figure 7. The ranges $0.1 \leq f \leq 0.2$ and $0.7 \leq f \leq 1$, which are outside the normal operating range, are shown in dashed lines. If the main load and the aircraft warning lights are connected as the minimum load, the part of the curve in stronger solid lines applies. Figure 8 shows the annual cost, P*, under the same conditions. / 116

5.3 Evaluation of the Cost Comparison for Power Supply to a Radio Directional Station

Under the conditions selected for the example, to be sure, the power generation costs, P, are nearly equal in the normal operating range (0.54 DM/kWh to 0.81 DM/kWh for the Diesel unit and 0.56 DM/kWh to 0.78 DM/kWh for the tungsten carbide/carbon

fuel cell) if one considers the minimum load for the fuel cell to be the main load and the aircraft warning lights. But in judging the cost for the Diesel unit one must also consider that below the limit for the additional load the power generation can be considerably greater than the useful load consumed. Thus, the power generation costs rise considerably, in relation to the useful load, as compared to the values plotted in the figures. The extreme case of minimum generation of 5 kW for an effective useful load of 0.285 kW was already mentioned in Section 5.1.2. In comparison to the Diesel unit, the fuel cell battery needs no minimum load and, then, no "artificial loading". This is expressed in the Annual costs.

Figure 8 shows the great difference in the annual costs of power production for the radio directional station with Diesel units as compared to fuel cells. Even if the tungsten carbide/carbon fuel cell were made much larger so that it could supply other loads, significant cost savings are given for use of fuel cells.

REFERENCES

1. Pohl, F. A., H. Böhm and H. Carl. Calculation and Comparison of the Efficiency of Electrochemical Fuel Cells. Wiss. Ber. AEG-TELEFUNKEN. Vol. 45, No. 3, 1972, pp. 141 - 146.

2. Lueckel, W. J., L. G. Eklund and S. H. Law. Fuel Cells for Dispersed Power Generation. IEEE Power Engineering Soc. IEEE Winter Meeting. New York, Jan. 30-Febr. 4, 1972. Paper T 72 235-5.

3. Schellhorn, E. and E. Ungeheuer. Interruption-free Power Supply for Radio Directional Stations in Iran. Techn. Mitt. AEG-TELEFUNKEN Vol. 61, No. 4, 1971, pp. 223-226.

4. Ungeheuer, E. Interruption-free Power Supply for Radio Directional Stations in Venezuela. Techn. Mitt. AEG-TELEFUNKEN. Vol. 61, No. 3, 1971, pp. 171-174.

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